


Impact of marble powder amendment on hydraulic properties of a sandy soil**

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Received October 18, 2019; accepted February 17, 2020

Abstract. Marble powder is one of carbonate rock amendments that is used to improve soil reaction. We hypothesized that the powdered marble addition can cause favorable changes in hydraulic properties of sandy soils. Six levels of marble powder addition to an aridisol soil (0%; M0; 5%; M5; 10%; M10; 15%; M15; 20%; M20 and 25%, M25; by bulk volume) were analyzed in triplicate. The saturated hydraulic conductivity and soil water retention curves were obtained. Pore space properties were investigated using soil water retention curves, mercury intrusion porosimetry and scanning electron microscopy. The saturated hydraulic conductivity significantly decreased (between 83 and 97% for M5 and M25 respectively) and parameters α and n of the van Genuchten model significantly decreased in marble-amended soils. Both field capacity and permanent wilting point increased with the addition of marble powder. Plant-available water, increased significantly until 10% of marble powder application; higher percentages of application did not provide additional significant changes in the plant-available water. Pore space distributions from soil water retention curves parameters showed an increase in the pore size range and a decrease in the average pore size; pore space distribution from the scanning electron microscopy also showed the presence of a new family of dominant pore sizes which was not detected by the soil water retention curves parameters approach. It was concluded that the addition of marble powder can improve the ability of soil to store water providing an advantage for irrigation water management in water scarce environments. Further research will have to address the impact of marble powder amendment under field semi-arid conditions.

Keywords: saturated hydraulic conductivity, soil water retention curve, field capacity, plant available water, pore size distribution

INTRODUCTION

Plant growth strongly depends on soil which provides mechanical and nutrient support for plants as well as water. Sandy soils have been known as relatively poor plant substrates (Qi *et al.*, 2002), partly due to their hydraulic properties. Sandy soils conduct water fast and have a low plant-available water content. In sandy soils, water can easily transport nutrients and other substances to groundwater thus reducing the irrigation water and fertilizer efficiency and creating environmental issues (Hall and Bell, 2015; Zhang *et al.*, 2016; Porter *et al.*, 2018; Serio *et al.*, 2018; Biddau *et al.*, 2019).

Adding fine particles can change the soil structure and affect soil hydraulic properties (Stone, 1980a, 1980b; Ghodrati *et al.*, 1995; Yunusa *et al.*, 2011). The addition of fine particles to the sandy soil may increase its water-holding capacity. Adding fine material can stabilize sandy soils, which can prevent desert expansion and dust storms, which are important in arid and semiarid environments. Finally, it can increase the available nutrients in the soil (Joris *et al.*, 2013; da Costa and Crusciol, 2016) and improve plant productivity (Olego *et al.*, 2016; Tiritan *et al.*, 2016).

Soil amendments affect the entire spectrum of soil properties, and their effect has to be evaluated in several aspects. One of such aspects is the ability of soil to conduct and retain water. The saturated hydraulic conductivity and soil water retention curve (SWRC), are the soil hydraulic properties to be evaluated. Other soil properties, such as the plant-available water, the wilting point or the field capacity,

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**This work was partially funded by the project GRE17-12 from the University of Alicante (2018-2019).

can be inferred indirectly from the abovementioned SWRC data. The importance of these parameters in the agricultural water management is out of doubt.

There is a long history of sandy soil amendment studies, but the interest in the scientific community is far from decline. Eibisch *et al.* (2015) used pyrochars and hydrochars, and they revealed that soil hydraulic properties improved and plant available water increased. Volk *et al.* (2016) investigated the effect of a soil-grown biofilm on the sandy soil's hydraulic properties. Their results showed that, compared to the sandy soil, the amended soil had a stronger soil water retention. They also found that biofilm reduced the saturated hydraulic conductivity of the soil. Amoakwah *et al.* (2017) examined the effect of adding corn cob biochar to sandy loam soil. Their results indicated that the application of 20 t ha⁻¹ of biochar significantly increased soil water retention. Basso *et al.* (2013) reported that amending sandy soil with biochar increased its water-holding capacity. Auler *et al.* (2017) evaluated the liming effects on silty clay soil and reported that the addition of lime to the soil increased both the field capacity (FC) and the permanent wilting point (PWP), respectively. They also reported that the plant-available water content, PAW, assumed as the difference between FC and PWP, also increased. Barnes *et al.* (2014) studied the effect of biochar addition to sandy soil. They reported that in amended sandy soil, saturated hydraulic conductivity decreased by 92%. Banedschafie and Durner (2015) devised an experiment to study the effect of superabsorbent polymers addition to sandy soil. They revealed that with the addition of super absorbents, the plant-available water content increased.

Powdered carbonaceous rocks and shells are commonly used as soil amendments (Barros *et al.*, 2009; Remonsellez *et al.*, 2017; Holland *et al.*, 2018; Ratke *et al.*, 2018). One of such amendments is the marble powder that is generated as an industrial byproduct that results from the mining, sawing, shaping and polishing of marble (Brown *et al.*, 1959; Ashish, 2018; Khodabakhshian *et al.*, 2018). Using marble powder as a soil amendment also offers a solution of the environmental problems related to marble industrial waste disposal (Wang *et al.*, 2017; Ashish, 2018). Marble powder as soil amendment has been studied (*e.g.*, Marras *et al.*, 2010; Zumrawi and Abdalla, 2018), but the main objective has been to improve soil geotechnical characteristics. To the best of our knowledge, the effect of marble additions to sandy soil and its effect on soil hydraulic properties has not been studied so far. Therefore, the objective of the present work is to study the effect of marble addition to sandy soil on the soil hydraulic properties at the laboratory scale.

MATERIAL AND METHODS

Sandy aridisol soil was collected in an experimental plot that is located in the foothills of a calcareous relieve in the region of Alicante, Spain (38°37'10.8"N 0°49'20.2"W). Undisturbed samples in 8-cm Ø steel rings were collect-

ed at the 30-cm depth; additional disturbed samples were collected at the same depth. Marble powder was collected from one of the waste sites in the municipality of Novelda, Spain (38°25'52.2"N 0°46'48.4"W).

The bulk density (Grossman and Reinsch, 2002) and mean total porosity (Flint and Flint, 2002b) were determined for the sandy soil; the particle size distribution (Gee and Or, 2002) and soil particle density (Flint and Flint, 2002a) were determined for both the sandy soil and the marble powder. The mineralogical composition of soil and marble powder were obtained analyzing crushed samples (<63-µm size) with powder X-ray diffraction (XRD) by using a D8-Advance diffractometer (Bruker, Germany) with a Goebel mirror (nonplanar samples) using Cu Kα radiation. The scanning range was from $2\theta = 1$ to 80°. Data were collected and interpreted using X Powder© software v.12 (Martin Ramos, 2004). The semi-qualitative search-matching procedure was based on the ICDD-PDF2 database. The analysis of trace elements in the marble powder was carried out to detect the potential presence of heavy metals and compare them with standards for plant growing media according to the European Commission decision 2015/2099. The heavy metals concentration analysis was performed with ICP-MS after an acid digestion, which uses combination of hydrochloric, nitric, perchloric and hydrofluoric acids. The marble industry produces water solution with the marble powder suspended and it uses chemical products to accelerate the sedimentation process so the presence of heavy metals in the marble powder should not be disregarded.

The original soil (M0, 0% of marble) and the soil with five different levels of marble addition (5%, M5; 10%, M10; 15%, M15; 20%, M20 and 25%, M25; by bulk volume) were employed in this study, yielding 6 treatments. We maintained the porosity equal to 35% to define the different levels of mixtures; *e.g.*, 5% mixture means that 5% of the solid phase volume was a substitute by the same volume of marble powder. Small differences in the bulk density existed because of the difference in particle density between the marble powder and the sandy soil particles. The original sandy soil was air-dried, <2 mm sieved, and used to create three replications for each mixture level.

Marble powder was mixed manually with the sandy soil for each sample. Each sample was packed into 250 cm³ stainless steel cylinders (5 cm height and 8 cm diameter). To achieve uniform bulk density, the soil samples were packed with consistent force in five equal increments. To make sure that the samples were homogeneous after adding each fifth of the sample to the cylinder, the remaining soil was mixed again before adding the next fraction.

Soil and soil-marble powder mixtures in cylinders were saturated from bottom to the top. The saturated hydraulic conductivity (K_s), was obtained in the laboratory using the KSAT apparatus (UMS® company) under the falling head condition.

Next, the soil water retention curve, SWRC, data was obtained using Hyprop (UMS® company). Hyprop measures the soil water content and the pressure head between saturation and the air entry value by using the extended evaporation method (Schindler *et al.*, 2010a,b). The tensiometer shafts and the sensor unit were filled with deionized and degassed water. The evaporation experiments were initiated at $h=0$ cm pressure head at the top of soil sample.

The saturated samples were placed on the Hyprop device and were exposed to evaporation in the laboratory. The evaporation process was accelerated by using a fan. The experiments were conducted at the room temperature ranging from 20-25°C. Depending on treatment, the upper tensiometer reached the air entry value after 5-11 days. At the end of experiment, soil samples were oven dried at 105°C for 24 h.

The bimodal version of the van Genuchten model, BVGM (van Genuchten, 1980), as described by Durner (1994), was adopted to model soil water retention:

$$Q(h) = Q_r + \frac{(Q_s - Q_r)w}{(1 + (\alpha_1 h)^{n_1})^{1-1/n_1}} + \frac{(Q_s - Q_r)(1-w)}{(1 + (\alpha_2 h)^{n_2})^{1-1/n_2}}, \quad (1)$$

where: h is water the pressure head (cm); θ , θ_r and θ_s are the actual, residual and saturated volumetric water contents ($\text{cm}^3 \text{ cm}^{-3}$), respectively; α (cm^{-1}) and n (dimensionless) are the pore size distribution parameters; and w is a weighting factor. Subscripts 1 and 2 denote porosity subsystems. The bimodal version of the van Genuchten model is recommended for soils with heterogeneous pore systems that cannot be adequately described by the unimodal version of the van Genuchten model (Eq. (1) with $w=1$) was also used. In the present study, two very different solid materials were mixed, therefore we considered that heterogeneous pore systems should not be disregarded. Both uni- and bi-modal versions of the van Genuchten model were tested and the bimodal alternative were chosen because it provided a better fit to the observations.

For all samples, the initial water content was approximately 1% less than the porosity, which was probably due to the entrapped air (Dettmann *et al.*, 2014). The van Genuchten SWRC fitting parameters θ_r , α_i and n_i were obtained by applying the generalized reduced gradient algorithm (Abadie and Carpentier, 1968; Lasdon *et al.*, 1978), to minimize the sum of the root mean square error between the observed and predicted values. The FC and the PWP were considered as the soil water contents at the water potential equal to 10 and 1500 kPa, respectively (Mylavarapu and Zinati, 2009; Jeffery *et al.*, 2015).

The pore size distribution (PSD) was quantified following two different approaches. First approach uses the fitted parameters for the BVGM obtained from the SWRC fitting process (above mentioned) and the Jurin's law (Eq. (2)) to relate the soil water pressure head and the soil pore sizes. The Jurin's law is based on the Young-Laplace equation:

$$h = \frac{-2\sigma \cos\theta}{\rho_w g r}, \quad (2)$$

where: θ is the contact angle between the soil porous and the water (assumed equal to 0° in this study); σ is the water surface tension (N m^{-1}); ρ_w is the density of water (kg m^{-3}); g is the gravity acceleration (m s^{-2}); r is the pore radius (m); and h is the absolute value of the soil water pressure head (m). The pore distribution density was then obtained indirectly.

The second approach to obtain the pore size distribution uses the mercury intrusion porosimetry (MIP) technique and the Washburn's equation, based on the Young-Laplace equation, to later transform the results of MIP into soil pore sizes. The pressure is inversely proportional to the size of the pores, and only slight pressure is required for mercury to intrude into large macropores, whereas much greater pressure is required to force mercury into small pores. In porous medium, mercury intrusion is similar to air injection in a saturated soil in the drying process of a water retention curve (Prapaharan *et al.*, 1987; Romero *et al.*, 1999; Aung *et al.*, 2001; Simms and Yanful, 2001; Zhang and Li, 2010; Mascarenha *et al.*, 2011; Otalvaro *et al.*, 2016). A PoreMaster 60 GT (Quantachrome Instruments) mercury porosimeter was used, and a surface tension and contact angle of mercury of 480 mN m^{-1} and 130°, respectively, were chosen. The pore diameter interval ranged from 0.002 to 200 μm , which corresponds to the highest (410 MPa) and lowest (1 kPa) head pressures. The samples were analyzed after determination of the saturated hydraulic conductivity and the soil water retention curve tests.

Microstructural characterization was performed using scanning electron microscopy (SEM), which permits the observation of the soil structure and provides clues to understand and explain the observed changes in soil hydraulic properties. Samples were observed in low-vacuum mode (voltage of 5-30 keV) with a Hitachi S3000N microscope. SEM images were taken at 50x magnification. At this low magnification, the low-vacuum mode provides excellent images without coating the sample. The samples were analyzed after the saturated hydraulic conductivity and soil water retention curve measurements. The samples were laterally sealed to obtain undisturbed samples and then were placed in the holder for analysis.

Soil hydraulic properties were analyzed using the SPSS 24 statistical package. Treatment means were compared by using Duncan's test at a significant level of $p < 0.05$ and $p < 0.01$.

RESULT AND DISCUSSION

Selected physical and mineralogical properties of the original sandy soil and marble powder are presented in Table 1. Content of selected heavy metals by the EU 2015/2099 Decision (European Union, 2015) was always below the maximum limits (Table 2) and was even below the detection limit or just non-detected in three out of seven target heavy metals.

Table 1. Physical and mineralogical properties of the original sandy soil and the marble powder

Samples	Sand	Silt	Clay	Texture	Bulk density	Particle density	Mineral composition (%)			
	(%)				(g cm ⁻³)		Calcite	Dolomite	Quartz	Feldspar
Soil	88.0	5.0	7.0	Loamy sand	1.62	2.62	17	–	61	22
Marble	0.0	57.7	42.3	Silty clay	–	2.67	63	36	1	–

Table 2. Content of heavy metals in the marble powder and limits of these components according to EU 2015/2099 Decision

Elements	EU limits	Marble powder
Cadmium (Cd)	3	0.16
Chromium total (Cr)	150	3.0
Copper (Cu)	100	6.2
Mercury (Hg)	1	NA
Nickel (Ni)	90	1.5
Lead (Pb)	150	2.4
Zinc (Zn)	300	6.0

NA – not analyzed.

The percentage of sand in the amended soil decreased jointly with an increase in clay and specially in silt. Percentages passed from 88/5/7 (sand/silt/clay) to 65-7/18.4/15.9 for the M0 and M25 treatments respectively (Table 3). Since the marble powder was added under the premise of

keeping the pore volume constant, the bulk density varied slightly among the different treatments because of the different values in the soil particle density between sandy soil and marble powder (Table 3).

The saturated hydraulic conductivity (Table 4) decreased after marble addition for all treatments. Compared to the control (M0), the marble powder application decreased the saturated hydraulic conductivity by 83, 90, 93, 95 and 97% for M5, M10, M15, M20, and M25, respectively. Barnes *et al.* (2014), who studied soil amendment by biochar, also reported that using 140 t ha⁻¹ biochar decreased sandy soil's saturated hydraulic conductivity by 92%. Volk *et al.* (2016) also found that biofilm amended sandy soil reduced the saturated hydraulic conductivity.

The fitted parameters from the BVGM (Eq. (1)) for all six treatments are shown in Table 4 and Fig. 1. Additionally, the soil water retention data for the three replications and six treatments jointly, with the fitting curves from the bimodal and unimodal van Genuchten models were included in

Table 3. Percentage of sand, clay and silt (mass-based), bulk density and texture

Soil property	Treatments					
	M0	M5	M10	M15	M20	M25
Sand	88	83.5	79.1	74.6	70.1	65.7
Silt	5.0	7.7	10.3	13.0	15.7	18.4
Clay	7	8.8	10.6	12.4	14.2	15.9
Bulk density (g cm ⁻³)	1.619	1.621	1.622	1.624	1.625	1.626
Texture	Loamy sand	Loamy sand	Sandy loam	Sandy loam	Sandy loam	Sandy loam

Table 4. Saturated hydraulic conductivity and van Genuchten soil-water characteristic curve fitting parameters

Parameters	Treatments						ANOVA
	M0	M5	M10	M15	M20	M25	
K _{sat} (cm day ⁻¹)	117.5 ^{a+}	20.1 ^b	12.0 ^{bc}	7.7 ^{bc}	6.1 ^c	3.4 ^c	**
θ _s (%)	33.7 ^a	35.1 ^a	34.3 ^a	34.0 ^a	33.7 ^a	34.0 ^a	ns
θ _r (%)	4.5 ^b	6.3 ^b	6.4 ^b	7.5 ^{ab}	8.2 ^{ab}	12.1 ^a	*
α ₁	0.017 ^a	0.016 ^a	0.015 ^a	0.015 ^a	0.013 ^{ab}	0.011 ^b	**
n ₁	4.5 ^a	2.3 ^b	1.7 ^b	1.6 ^b	1.6 ^b	1.6 ^b	*
w	0.49 ^a	0.51 ^a	0.61 ^a	0.64 ^a	0.63 ^a	0.61 ^a	ns
α ₂	0.018 ^a	0.017 ^{ab}	0.015 ^{ab}	0.015 ^{ab}	0.015 ^{ab}	0.014 ^b	*
n ₂	5.6 ^a	5.2 ^a	5.0 ^a	4.8 ^a	4.6 ^a	4.3 ^a	ns

+Values in the same row with the same letter are not significantly different at p<0.05 level. Statistically significant at: *5% level, **1% level.

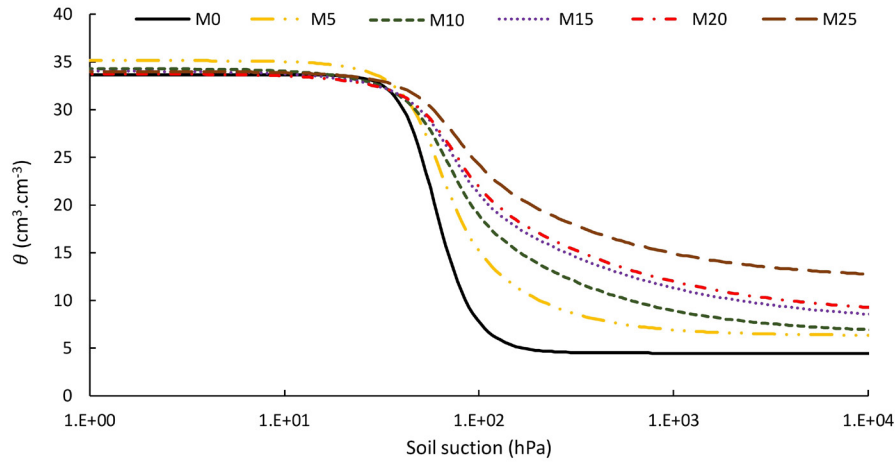


Fig. 1. Average soil water retention curves for the original soil and the five levels of marble additions. The numbers indicate the percentage of marble powder added to the original sandy soil.

the Supplementary Material file (Fig. S1). Both uni- and bimodal options provided a good fit during the wet and middle parts of the curves; nevertheless, the bimodal option was more flexible and better fitted the dry part, with the pressure head below 200 hPa, so the bimodal option results were selected and further discussed. The θ_s parameter showed only slight differences that were not statistically significant. These differences could be attributed to process errors, because all the mixtures were initially designed to have the same total porosity. Regarding the residual water content (θ_r), a monotonic and statistically significant increase was observed with increasing percentages of marble addition, which can be explained by the increase in the percentage of fine soil particles and then the increase in the specific surface of the mixture. The increment in θ_r was more pronounced in M15, M20 and M25. The θ_r in M25 was approximately three times higher than that of the original sandy soil. Addition of marble powder more than 10% changed the soil texture from sandy loam to loamy sand.

The shape parameter α decreased significantly and monotonically with marble powder addition from 0.018 to 0.013 (cm^{-1}) for the original sandy soil and M25, respectively. Parameter α is related to the air entry pressure (Peters and Durner, 2008); the lower α is, the higher the air entry pressure becomes. The addition of marble powder significantly increased the air entry pressure. Parameter α also determines the position of the maximum pore density (Durner, 1994), which decreased with the increase of marble powder (Figs 2 and 3).

Parameter n is related to the pore size distribution; the narrower the pore size distribution is, the larger the n (Peters and Durner, 2008). The average fitted SWRCs (Fig. 1) shows the impact of those parameter changes (Jury and Horton, 2004). The figure also shows the original SWRC (black line) and the SWRCs for all levels of marble powder addition. All the above-mentioned comments are graphically collected in the figure, which shows the gradual evolution of curves with more gradual transitions between

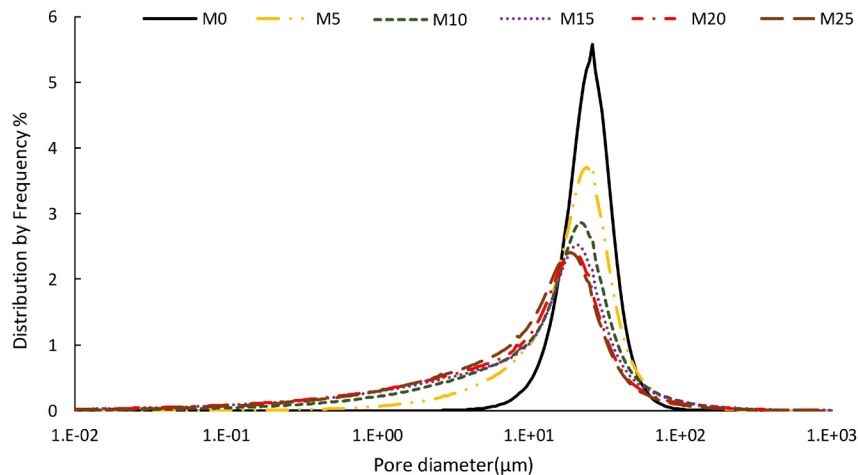


Fig. 2. Pore size density functions from the van Genuchten model parameters for the different treatments.

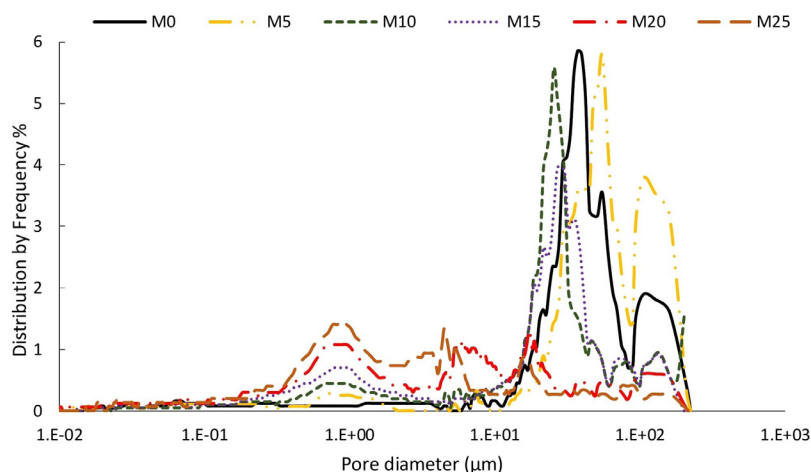


Fig. 3. Pore size distribution curves from mercury intrusion porosimetry for different treatments.

the higher and lower water contents. The sandy soil, which had higher percentages of large pores and a smaller range of pores, yielded curves with substantial decreases of water content in relatively narrow ranges of the soil pressure head. In marble-powder-amended soils, this feature was modified by producing a wider range of pore sizes (Figs 2 and 3), which caused a gradual reduction of potential gradient during the drying of the sample, thus indicating that narrow pores are more frequent. By keeping the total porosity constant, potential differences among samples should be attributed to differences in the grain size distribution, which causes changes in the pore size distribution. By increasing the percentage of marble powder in the mixture, the percentage of very small pores increased and marble powder blocked the larger soil pores, which mainly contribute to a large proportion of the water flux in the soil.

The root mean square error (RMSE) for SWRC obtained using Hyprop and fitted SWRC with the bimodal version of the van Genuchten model (Table 5) indicated that the fit was acceptable as the reported average RMSE values for all fittings were equal to 2% and always below 4%; these values are similar to the errors of typical soil moisture measurement reported by the industry (Decagon Devices Inc, 2010; Campbell Scientific, 2012).

PSD obtained using the fitted parameters from the BVG model and the Jurin's law (Fig. 2) revealed that the addition of marble powder to sandy soil reduced the mean

pore size, and increased the spread of pore sizes, *i.e.*, with marble powder addition the soil presented a larger more extended range of pore sizes. The most important increase in the spread of pores sizes appeared with additions of low percentages (5 and 10%); on the other hand, the differences in the pore size distributions for the M20 and M25 treatments were insignificant. The PSD obtained from the second approach, using the MIP technique (Fig. 3), shows that M0 had most of pores in the pore diameter interval of 10–200 μm , and the dominant (*i.e.* the most frequent) pore diameter in M0 was approximately 40 μm . The increase in added marble powder produced a monotonic reduction in the dominant pore diameter, with additions equal or higher than 10%. In the case of 5% of addition, there was not detected a clear reduction in the dominant pore size. In general, the dominant pore diameter decreased from 40 μm in M0 to 1 μm in M20 and M25. Focusing on the complete pore size spectrum besides the dominant size, M0 can be defined as a single grain structure (sorted soil); nevertheless, the M5 to M25 treatments produced bimodal pore size distributions. Results demonstrates that the percentage of pores in the 0.5–10 μm interval increased with the marble powder addition (Fig. 3).

There is relatively good agreement between the pore size distributions obtained from water retention and from mercury porosimetry. Both methods resulted in the dominant pore size in the range 30–50 μm for the original sandy soil, and both considered that the pore distribution density moved to smaller pore sizes with the increasing addition of marble powder. The dominant pore diameter for M20 and M25, inferred from the fitted parameters (first approach) was higher than the value that was reported by the MIP data. The most important disagreement between the two methods was the presence of two families of dominant pores in MIP results but not in SWRC data. The width of the PSD obtained from SWRC moved toward a fine pore size with the increasing addition of marble powder. This disagree-

Table 5. RMSE between observed and simulated soil pressure head for all treatments and replications considering the bimodal van Genuchten model (Eq. (1))

Replica- tions	Treatments					
	M0	M5	M10	M15	M20	M25
1	0.03	0.02	0.01	0.02	0.02	0.02
2	0.04	0.03	0.02	0.01	0.02	0.02
3	0.02	0.02	0.02	0.02	0.01	0.01

ment in the presence of one or two families of dominant pores was more pronounced with the highest percentage of marble powder addition. The different scales that both methods operate at, with distinctly smaller samples in the case of MIP compared to the sample size that is needed for the Hyprop apparatus, could explain this disagreement. Romero *et al.* (1999) reported that the MIP predictions significantly underestimated the water contents of a clay soil at suctions higher than 400 hPa, which occurred at pore diameters smaller than 7 μm . The good fit obtained using the unimodal van Genuchten (Supplementary Material file) showed that the bimodal structure of the pore size distribution was not expressed well in the soil water retention curve.

Both FC and the PWP increased with the increasing addition of marble powder. Nevertheless, the increasing trend was different between FC and PWP and as a consequence PAW, obtained as the difference between field capacity and permanent wilting point, showed a maximum value of 12.73% with marble powder percentages of 15% (Fig. 4 and Table 6). This result constitutes an increase of 120% from the value of PAW in the original sandy soil (*i.e.* 5.78% for the original soil). The increase in the PAW was more important in the percentages of addition up to 10% (Fig. 4). Actually, the PAW results from M10, M15, M20 and M25 showed no statistically significant differences. On the contrary, results from M0 and M5 did show statistically significant differences between them and between each of them and the M10-M15-M20-M25 group (Table 5). The PAW is one of the most important parameters in irrigation and drainage system design, and increasing PAW on a large scale could help to save water and energy, very important in water-scarce societies. The results showed that the most

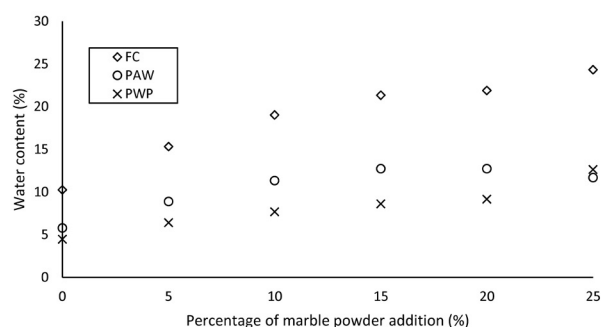


Fig. 4. Field capacity (FC), plant available water (PAW) and permanent wilting point (PWP) for the original soil and the five treatments.

Table 6. Average field capacity (FC), permanent wilting point (PWP), and plant available water (PAW) for the different treatments

Treatments	M0	M5	M10	M15	M20	M25	ANOVA
FC (%)	10.2 ^{c+}	15.3 ^{bc}	19.0 ^{ab}	21.3 ^{ab}	21.9 ^{ab}	24.3 ^a	**
PWP (%)	4.5 ^b	6.4 ^{ab}	7.7 ^{ab}	8.6 ^{ab}	9.2 ^{ab}	12.6 ^a	**
PAW (%)	5.8 ^c	8.9 ^b	11.3 ^a	12.7 ^a	12.7 ^a	11.7 ^a	**

Explanations as in Table 4.

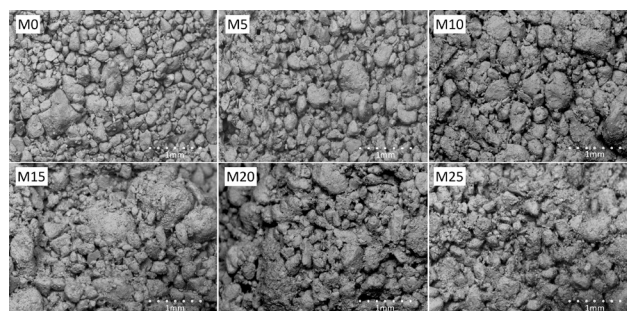


Fig. 5. Scanning electron microscope images for different treatments at the 50x magnification. The numbers indicate the percentage of marble powder added to the original sandy soil.

promising percentage of addition is 10% because it leads to the highest increases in PAW with the lowest percentage of marble powder addition.

The SEM results of specimens are shown in Fig. 5. It can be observed that, as the percentages of marble powder in the mixture increase, there is a gradual process of filling of the small pores that are clearly identified in the M25 image but are less common in the M0 image. The soil particles in the original soil (M0) are coated by other much smaller particles increasing the specific surface and providing a graphical explanation for the increase in soil water retention (Fig. 5).

Marble powder appear to be located in the intergrain pores of the original soil, thus reducing the effective space for water flow, which explains the reduction in saturated hydraulic conductivity. As a consequence, marble powder connect the original soil particles together, fills larger pores and creates a finer structure of pores, which also explains the variation in the van Genuchten parameters, field capacity, permanent wilting point and plant available water.

CONCLUSIONS

Although marble powder-amended soils have been studied before, to the best of our knowledge, this is the first study on the potential improvement of sandy soil hydraulic properties with the addition of marble powder. From our results, we can conclude:

1. A significant decrease in saturated hydraulic conductivity as a result of marble powder addition to sandy soil.
2. The addition of marble powder decreased the soil pore size and had a great impact on the soil water retention behaviour.

3. The range of pore sizes in amended soils increased, and the abrupt changes in the soil water content with small changes of the soil pressure head, which were observed in the original soil, disappeared giving place to more gradual changes in the water content.

4. The bimodal van Genuchten model provided a better fit to the observed water retention data than the unimodal van Genuchten model. However, it is worthy to note that the unimodal model fit was also good and that the main differences appeared in the dry part of the curve, with pressure heads below -500 hPa.

5. The MIP results showed the presence of a wider range of pore sizes in the amended soil and the presence of two main families of pore sizes. This presence of two main families of pore sizes was not surmised from the fitted parameters of the bimodal van Genuchten model.

6. As the added percentage of marble powder increased, the retention curve moved toward the domain of higher pressure head values, thus increasing the air-entry value. This shift of the soil water retention curve can be attributed to the increment in the pore size range. All α_i and n_i parameters from the van Genuchten model, decreased in the marble-amended soil.

7. The permanent wilting point and the field capacity significantly increased. Nevertheless, the increase trend in field capacity was different than that for the permanent wilting point, and therefore the plant-available water significantly increased up to 15% percentage and showed a reduction trend with higher percentage of additions; it was not detected significant difference in the PAW for the percentages of 10, 15, 20 and 25%. This improvement in the plant available water provides a potential benefit for agriculture management in water-scarce environments.

7. Since the statistically significant differences for PAW occurred with percentages of addition below 10%, further investigation should focus on the impact of lower percentages of the marble powder additions. Investigating the impact of adding lower percentages of marble powder could assist in determining the optimum percentage of marble powder to improve sandy soils across large areas.

Further studies, especially under field conditions, should be conducted to investigate the effect of marble addition on sandy soil hydraulic properties on a larger scale.

Conflict of interest: The Authors do not declare conflict of interest.

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SUPPLEMENTARY MATERIAL

Impact of marble powder amendment on hydraulic properties of a sandy soil

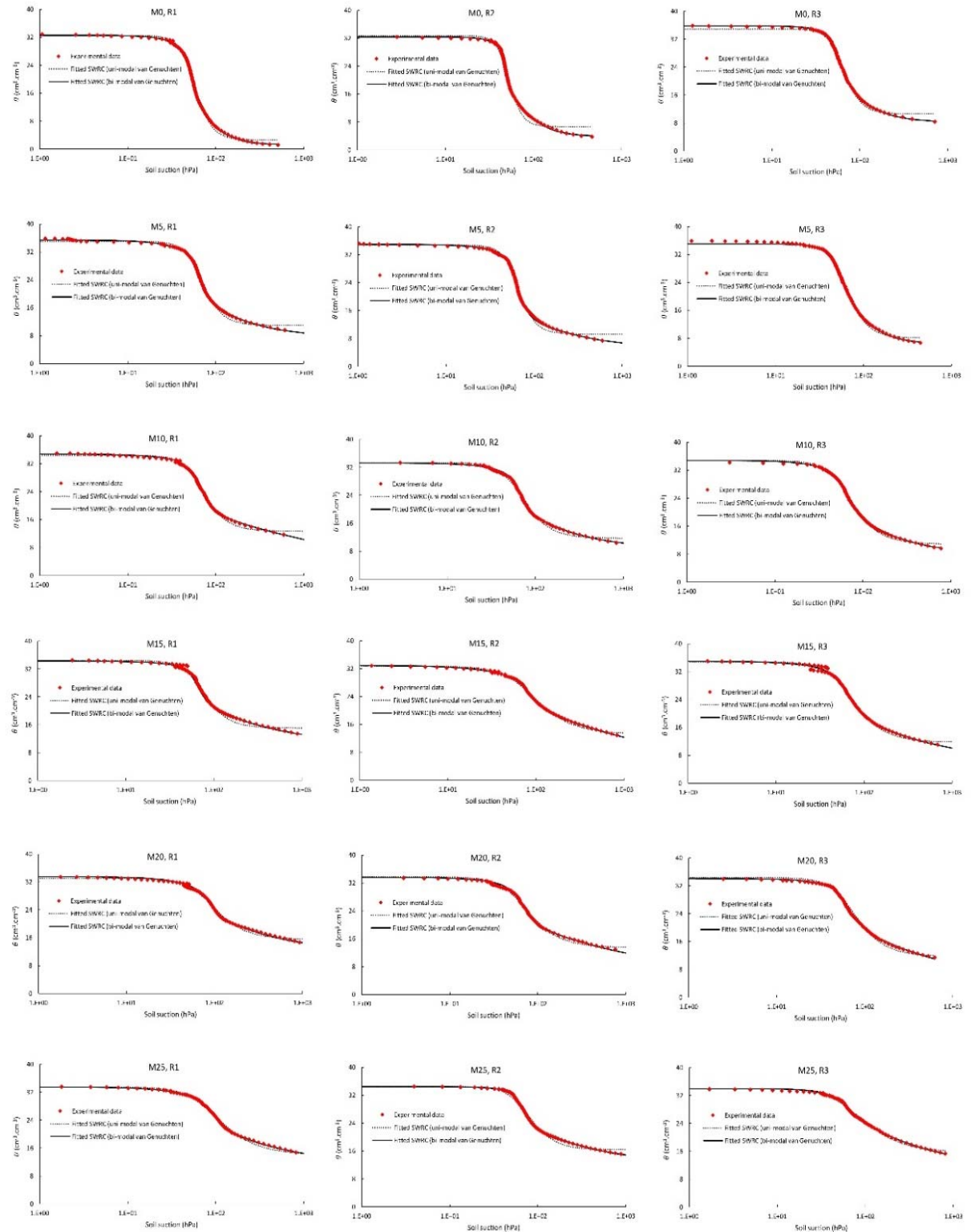


Figure S1. Soil water retention curve data and fitted uni- and bi-modal van Genuchten models for the three replications of the original soil and the five levels of marble.